STATISTICAL DETERMINATION OF SAFETY FACTOR REQUIREMENTS FOR UNTESTED STRUCTURES FROM SATURN V TEST DATA

By

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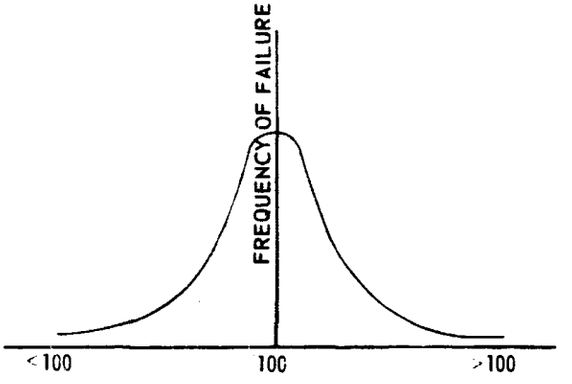
INTRODUCTION

A traditional method of assuring structural reliability in aircraft, missiles, spacecraft, and launch vehicles is the application of structural safety factors. These safety factors must always be carefully defined to meet the needs of the particular system; but for our purposes, it is sufficient to define the safety factor as the ratio of the load required to produce failure in a structure to the maximum expected load in service (limit load). Typical safety factors in the aerospace industry range from 1.2 to 1.5 for major structures. It is standard practice to test a specimen of every major structure to assure that the required safety factors do exist.

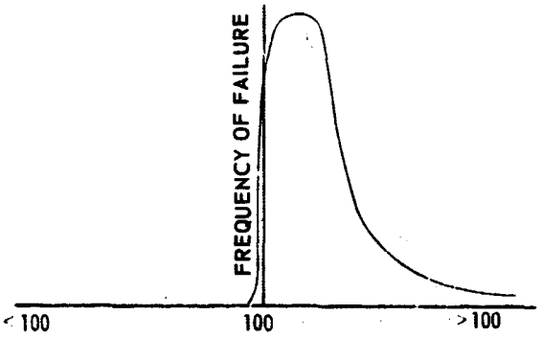
The increasing size and complexity of aerospace structures, coupled with the more complex combinations of environments, cause the cost of testing and the influence of the testing on overall development schedules to continually increase. This provides sufficient motivation to search for ways to minimize the test program. Is it possible to decrease the scope of required testing to gain cost and schedule advantages without sacrificing the all important system reliability? In the large systems of the immediate future, such as the Space Shuttle and Space Station, certain structures will almost certainly be sized by stiffness requirements from dynamic considerations or by long life requirements. Thus, these structures may have an inherently large safety factor on the maximum expected load. In other systems, it may be feasible to increase the safety factor to some desired level at the expense of adding weight. The purpose of this paper is to illustrate a possible method for determining what safety factor is required to provide reliable structures without testing.

DESCRIPTION OF METHOD

There will always be inaccuracies in predicting the failure load of any given structure. It is reasonable to expect that the failure load will be overpredicted in some cases and underpredicted in others, with most structures failing near the predicted value and with a decrease in the probability of failure at load levels either above or below the predicted level. As will be shown later, the distribution of failure frequency about a mean value (near the predicted value) is approximately normal for Saturn V structures. This is illustrated schematically in Figure 1a. Design changes are usually made in those structures that fail at less than the predicted level while those that fail at or above the predicted level are left unchanged. As a result, the failure frequency of structures that are actually used in flight would appear somewhat as illustrated in Figure 1b. This odd distribution would



a. Structures as tested



b. Structures after testing and repair

Figure 1. Schematic of failure frequency distributions.

then make a statistical prediction of probability of failure in flight very difficult, even if other important variables such as manufacturing differences and expected load uncertainties are ignored.

The concern of the present analysis is to accomplish the somewhat easier task of determining the safety factor for untested structures that will give essentially the same probability of success as that obtained with tested structures. This is accomplished by first assuming that the Saturn V structure is representative of the structural article under consideration. Statistical properties of the Saturn V test can be determined, and a normal distribution curve similar to Figure 1a can be constructed. Once this is done, a percentage of the predicted failure load can be determined for which a selected probability exists that the failure load of the article under consideration will exceed. From this percentage, the required safety factor can be determined to assure that the structural article will not fail at less than the ultimate load.

SATURN V TEST DATA ANALYSIS

Assumptions and Limitations

It is assumed that all structural components can be grouped statistically and that all tests were valid with respect to loads and environments. If a test specimen was not tested to failure, the maximum load sustained is taken as the strength of the specimen. If one test specimen was tested to a series of ultimate tests, the maximum load sustained in any test is taken as the strength.

Data Analyzed

A sample of the Saturn V test data that were analyzed is shown in Table 1. Basically, each data point represents one major Saturn V structural assembly such as a tank, interstage, or thrust structure. In some cases structural articles were subjected to more than one load condition. If these load conditions were very similar to each other, the maximum load sustained in any test was taken as the specimen strength. In other cases a single structural article was subjected to more than one test, and the test conditions were entirely different. In these cases more than one data point was gained from the single structural assembly.

TABLE 1. SATURN V TEST DATA

Data Point Number	Test Safety Factor	Percent of Predicted	Tested to Failure
1	1.40	100	No
2	1.58	113	Yes
3	1.12	80	Yes
4	1.65	118	Yes
50	1.41	101	Yes

Most of the Saturn V structures are made from high strength aluminum materials. The construction is a mixture of riveted skin-stringer, integrally stiffened, and sandwich articles.

The second column in Table 1 shows the safety factor attained by each article in the static structural test. This factor represents the ratio of the load attained in test to the limit load. The third column, which is the actual data analyzed, represents the percentage of the predicted capability load attained by the article. For purposes of this analysis, the predicted capability was taken as the limit load times the safety factor requirement for the article. An indication as to whether or not the article was tested to failure is given in the last column. Slightly more than half of the structures tested were tested to failure. The fact that some structures were not tested to failure produces an undesirable bias in the data, but this is not believed to be severe because many of the articles that did not fail were very near failure based on strain gage instrumentation.

Statistical Representation of Data

A statistical representation of the data is shown in Figure 2. The normal distribution was calculated by standard statistical methods. The histogram is shown to give a visual comparison of the actual data to the normal distribution curve. The data have a mean value of 0.99 and a standard deviation of 0.142. A more detailed representation of the statistical properties is shown in Figure 3. An example of conversion of the abscissa to any desired safety factor is shown on the (B) scale in Figure 3.

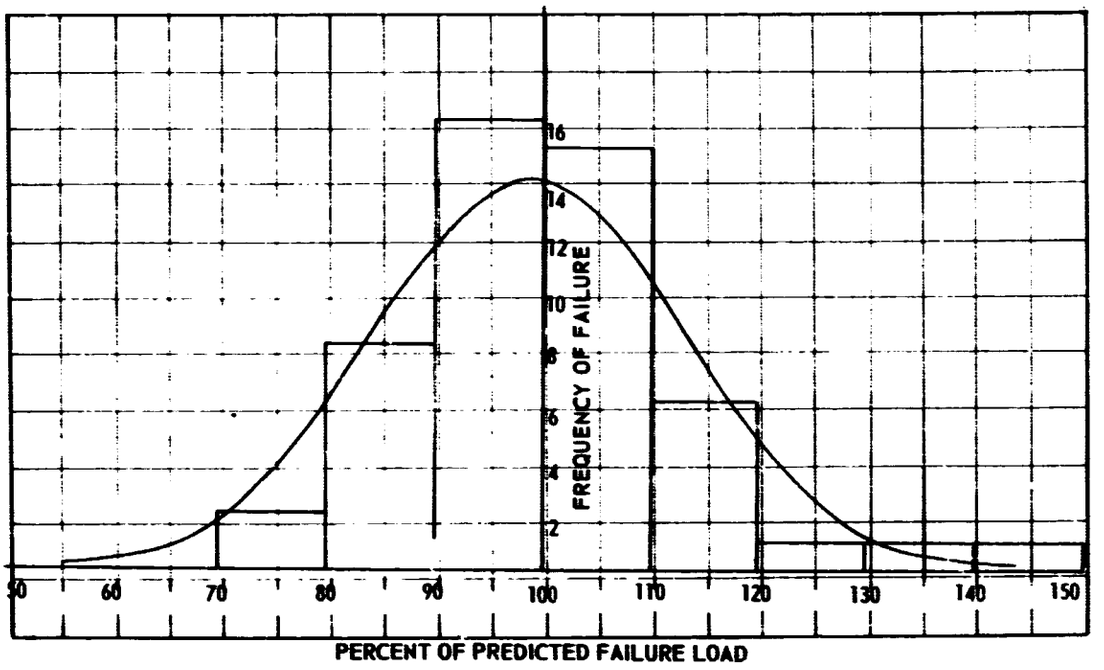


Figure 2. Saturn V test data — histogram and normal distribution.

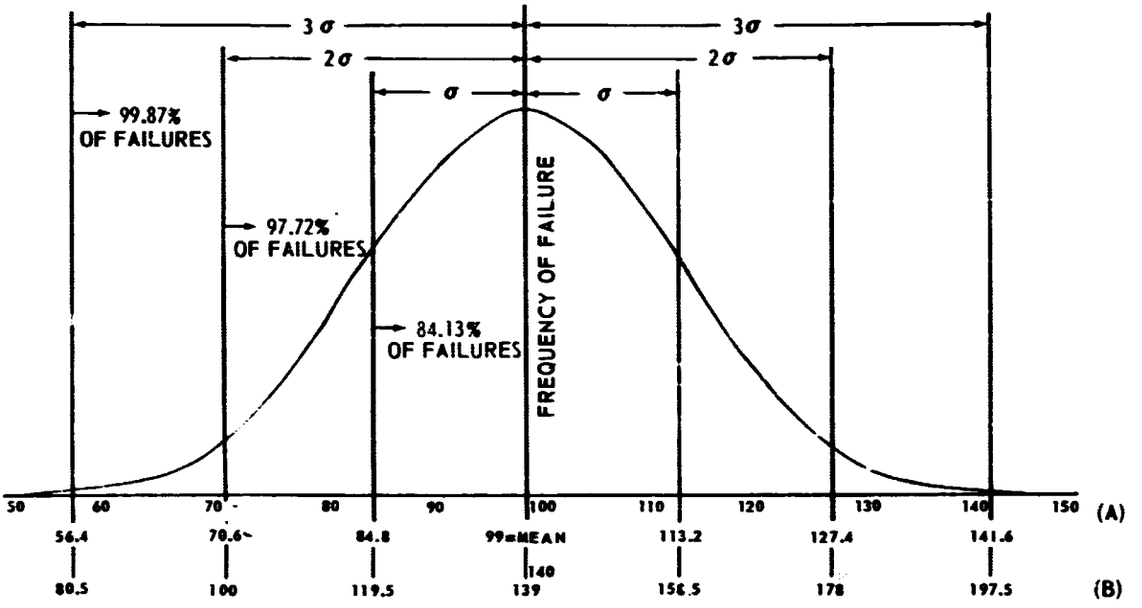


Figure 3. Predicted failure distribution of unterte: Saturn V type structures.

Analysis of Data

Let μ represent the mean of the test data. Then, the percentage of the expected failure load, which is Z standard deviations less than the mean value, is $\mu - Z\sigma$, where σ is the standard deviation. Thus, for untested structures, the ratio of the expected failure load to the actual failure load for a $Z\sigma$ probability is given by

$$R = \frac{100}{\mu - Z\sigma}$$

Then any desired value of failure load must be multiplied by this ratio to obtain a design load that gives a $Z\sigma$ probability of no failure at the desired failure load. If the safety factor of tested structures is represented by FS_t, the equivalent safety factor, FS_u, for untested structures would be given by

$$FS_u = R \times FS_t$$

In Figure 4, the required safety factor, FS_u, for untested structures has been plotted versus the probability of no failure, $Z\sigma$, for various values of FS_t as a parameter. It should be noted that the $FS_t = 1.00$ plot (represented by the 100 percent limit load curve) gives the probability of failure for untested Saturn V type structures at limit load. Figure 5 is a crossplot of Figure 4 from which the equivalence between safety factors for tested and untested structures can be determined directly for either a 2σ or 3σ probability of no failure.

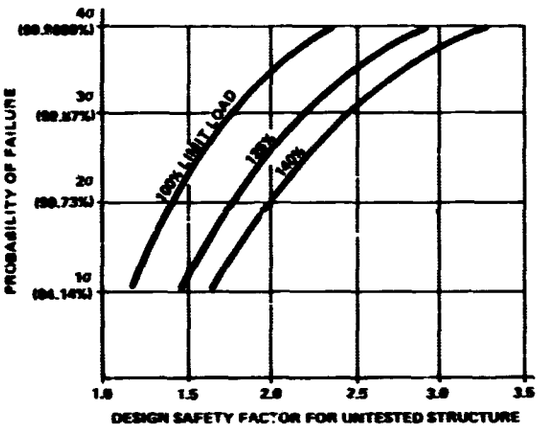


Figure 4. Failure probability prediction.

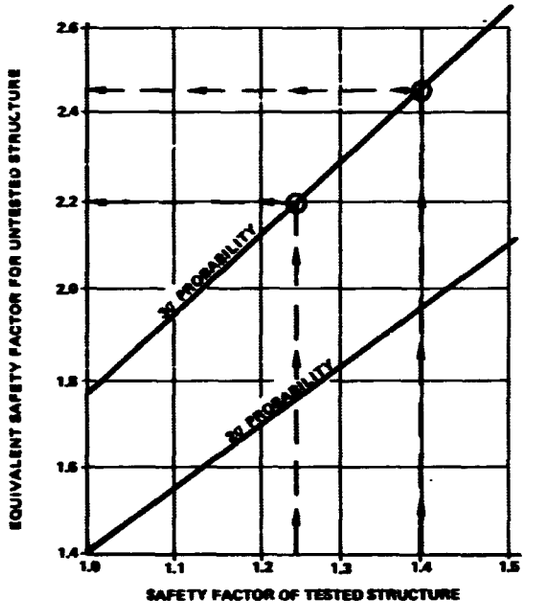


Figure 5. Equivalent safety factors.

CONCLUSIONS

Although the data presented should not be interpreted as absolute because of the assumptions made and the limited test data available, they seem to yield a rational guide for choosing safety factors for untested structures. For structures sized by stiffness considerations, life requirements, or minimum gage restraints or for structures for which weight is not of utmost importance, a no-test philosophy with larger analytical safety factors to provide equivalent reliability is worthy of careful consideration.